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Hybrid two-phase flow measurements in a narrow channel using neutron radiography and liquid film sensor

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Abstract

Gas-liquid two-phase flow in a narrow gap has been studied to develop a solid target cooling system for an accelerator driven system. Flow measurements are important to understand two-phase flow dynamics also in such a narrow channel. Although contact methods can measure detailed structure of two-phase flow, the intrusive effect on the flow becomes relatively larger in such a small channel. Therefore, non-intrusive measurement would be desirable. Neutron radiography (NRG) is one of the powerful tools for gas-liquid two-phase flow measurement and void fraction distribution can be estimated from the acquired images. However, the temporal resolution of NRG is about 100~1,000 Hz depending on the neutron flux and it should be increased to investigate flow dynamics. So the authors focused on a hybrid measurement of the NRG and a conductance liquid film sensor (LFS). The combination of these methods can complement the spatial and temporal information of the flow. In this study, the hybrid measurements were performed by NRG and LFS to visualize the detailed structure of narrow two-phase flow.

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Keywords: Gas-liquid two-phase flow; narrow channel; liquid film sensor; high frame-rate neutron radiography; hybrid measurement

1. Introduction

For development of an accelerator driven system (ADS) with a solid spallation target, the cooling techniques of the solid target should be optimized. In the solid target system, the narrow flow channels are formed between the target plates. To understand the coolability of the system, not only single phase flow but also gas-liquid two-phase flow structure in the narrow channel should be clarified. As a simple test, boiling two-phase flow in a one-side

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heated narrow channel was investigated by Kureta et al. (2001, 2003). They applied neutron radiography (NRG) to a narrow two-phase flow measurement and the void fraction distribution was obtained. In their results, although the bubble structure in the narrow gap was visualized, liquid film behavior on the heated surface should be investigated to clarify the boiling heat transfer characteristics for the solid target system. However, it is difficult to get depth information of the flow using NRG. Therefore, the present study focused on a hybrid measurement using NRG and a liquid film sensor (LFS) based on electrical conductance measurement. Fig. 1 shows schematics of the proposed hybrid measurement method in the one-side heated narrow rectangular channel. In the narrow channel, void fraction in the gap is measured by NRG. This void fraction can be considered as the thickness of the gas phase (bubble) in the gap. As the LFS is installed on the opposing wall of the heated surface, the film thickness distribution can be estimated on the non-heated wall. As a result, the film thickness on the heated surface is calculated from measured data by NRG and LFS, as follow.

$$\delta_{heat} = s - (\delta_{bub} + \delta_{film}) \quad (1)$$

where s is the gap distance of the narrow channel. The liquid film thickness on the heated surface is one of the most important parameter in boiling two-phase flow studies. The accurate measurement of the film thickness on the heated wall will be helpful for the improvement of the boiling heat transfer model and the development of the thermal-hydraulic simulation code. Thus, the final purpose of this study is to measure the liquid film behavior on the heated surface by means of the hybrid measuring technique. As a first challenge for this purpose, air-water two-phase flow measurements are carried out using both NRG and LFS. In addition, the possibility of the film measurement on a simulated heated surface is discussed.

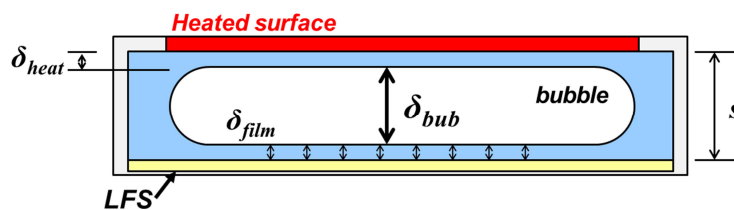


Fig. 1. Schematic of liquid film measurement on the heated surface (cross-sectional view of an one-side heated narrow rectangular channel).

2. Experiments

2.1. Experimental setup

Experiments are conducted at the B-4 experimental room in the Kyoto University Research Reactor (KUR) (Saito et al., 2011). The experimental setup is illustrated in Fig. 2. The width and gap of the channel are 12 mm and 2 mm, respectively. The test channel is made of acrylic resin and is placed vertically. Upward air-water two-phase flow is formed in the measurement section. Water is circulated by a pump and the flow rate is monitored by a rotameter. The electrical conductivity of water is about 200 $\mu\text{S}/\text{cm}$ during the experiments. Air is sent from a compressor and is injected at the upstream of the test section. The air flow rate is measured by a mass flow meter. A LFS is installed on a wall of the channel. The LFS measurement is performed with 7×32 measuring points. The neutron beam is irradiated to the same region as the measurement area of the LFS. The neutron beam has a width of 10 mm and a height of 75 mm at the beam exit and the neutron flux is $5 \times 10^7 \text{ n}/\text{cm}^2\text{s}$ at 5 MW operation mode of the KUR.

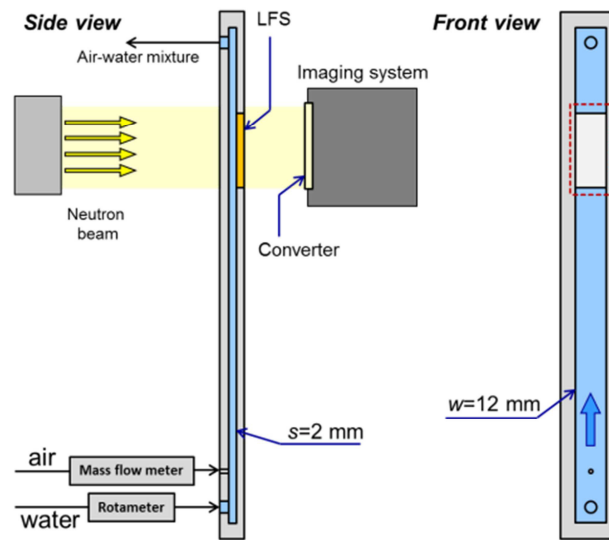


Fig. 2. Schematics of experimental setup.

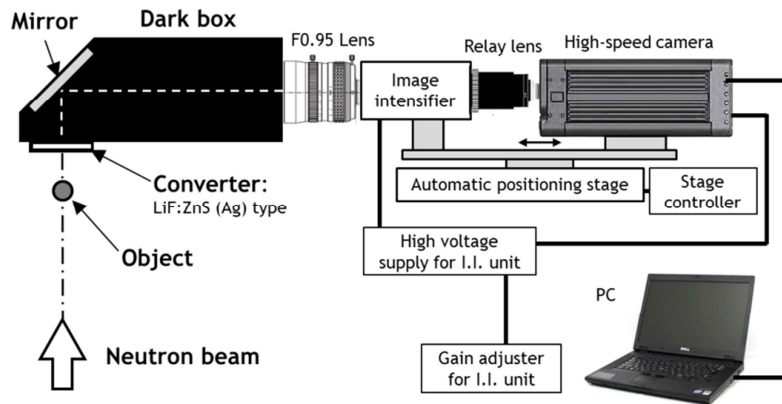


Fig. 3. Imaging system for high frame-rate neutron radiography.

The schematic view of the neutron imaging system applied in this study is presented in Fig. 3. This system has been developed to investigate the dynamics of the two-phase flow and it consists of a converter ($^6\text{LiF/ZnS:Ag}$), a high speed video camera (MotionPro Y4-Lite, IDT), an optical lens, an image intensifier (combination of a MCP and a Booster) and a dark box with a mirror. The image sequence taken by the high speed camera is saved on a PC and then the images are processed. The spatial resolution of the acquired radiographs is 0.16 mm/pixel. The high speed camera is synchronized with a high speed conductance measurement system for the LFS. The sampling rates of NRG and LFS are 200 Hz and 10,000 Hz, respectively.

2.2. Image processing for high frame-rate neutron radiography

Neutron radiographs include several noises. Such noises are mainly caused by the converter, the neutron scattering and the neutron beam divergence. Additionally, the object motion and the short exposure time are important factor to evaluate the noises in the high frame-rate NRG. Therefore, the acquired radiograph must be post-processed to enhance the image quality by applying digital filtering technique. In this study, the void fraction distribution is estimated from the neutron radiograph at first, and then the filtering method is applied to the void fraction image. Here, the void fraction is estimated from the image gray level of the acquired images of gas and liquid single phases and two-phase mixture by using Σ -scaling method (Mishima and Hibiki, 1996), as expressed in the following equations.

$$\alpha = \ln \left(\frac{G_L - G_0}{G_{LM} - G_0} \right) / \ln \left(\frac{G_L - G_0}{G_G - G_0} \right) \quad (2)$$

and

$$G_0 = \frac{G_L - G_G \cdot \exp(-\Sigma_L \delta_L)}{1 - \exp(-\Sigma_L \delta_L)} \quad (3)$$

where G , Σ and δ represent the pixel gray level, the total macroscopic cross section, and the thickness, respectively. The subscripts L , G and LM denote the liquid single phase, the gas single phase and the liquid phase in two-phase mixture, respectively.

Generally, the radiographs are filtered by using conventional spatial filter such as averaging filter and Gaussian filter. However, the dynamic image sequence acquired by the high-speed camera has spatio-temporal information. Thus, the spatio-temporal filter is available for the present void fraction data. In this study, non-local mean filter (Buades et al., 2005) is extended to three-dimensional region. This filter is classified as the edge-preserving method.

2.3. Electrical conductance liquid film sensor

The measuring principle of the LFS is based on a high speed electrical conductance measurement. The liquid film thickness on the sensor surface is measured from the electrical conductance between transmitter and receiver electrodes placed next to each other. A photo of the sensor surface is presented in Fig. 4 (a). The LFS used in this study consists of transmitter, receiver and ground electrodes, as shown in Fig. 4 (b). The distance between detecting electrodes and ground spots is 0.75 mm. Both transmitter and receiver electrodes have a diameter of 0.5 mm, and the ground electrodes have a diameter of 0.7 mm. Therefore, the total simple cell of the electrodes has the lateral dimensions of 1.5 mm, which is equivalent to the spatial resolution of the measurement using this LFS. The more details of the measurement using the LFS are described in the previous papers by Damsohn and Prasser (2009) and Ito et al. (2011).

3. Results

3.1. High frame rate neutron radiographs and spatio-temporal filtering

The typical neutron radiographs of two-phase mixture, liquid and gas phases in the narrow rectangular channel are shown in Fig.5. It is seen from the acquired radiograph that there are bubbles in the channel. The void fraction distributions estimated from Fig.5 (a)-(c) by using Σ -scaling method are represented in Fig.6 (a). High void fraction values indicate where the bubble exists, and the size of bubbles could be roughly estimated from the distribution. However, a lot of noises were found in the liquid phase region in Fig.6 (a). In addition, the bubble

region also has some noises, as shown in Fig.6 (b). Thus, the three dimensional non-local mean filter was applied to the estimated void fraction distribution. The distributions filtered from Fig.6 (a) and (b) are shown in Fig.6 (c) and (d), respectively. The remarkable noises were reduced by the filtering process. Although most of the noises were removed by the spatio-temporal filtering method, the filtering should be optimized for the accurate measurement of the thin liquid film behavior.

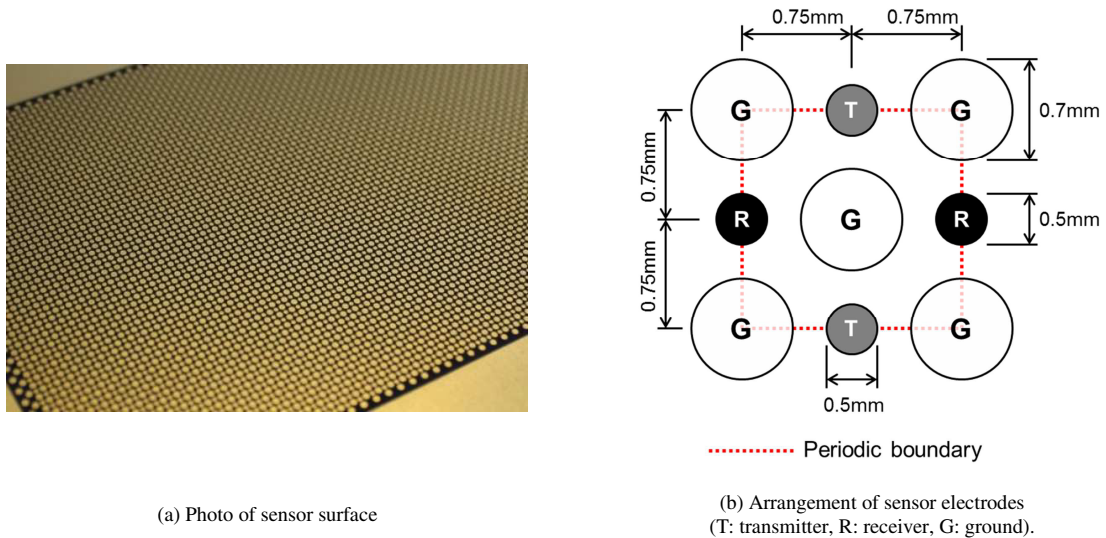


Fig. 4. Details of liquid film sensor used in this study.

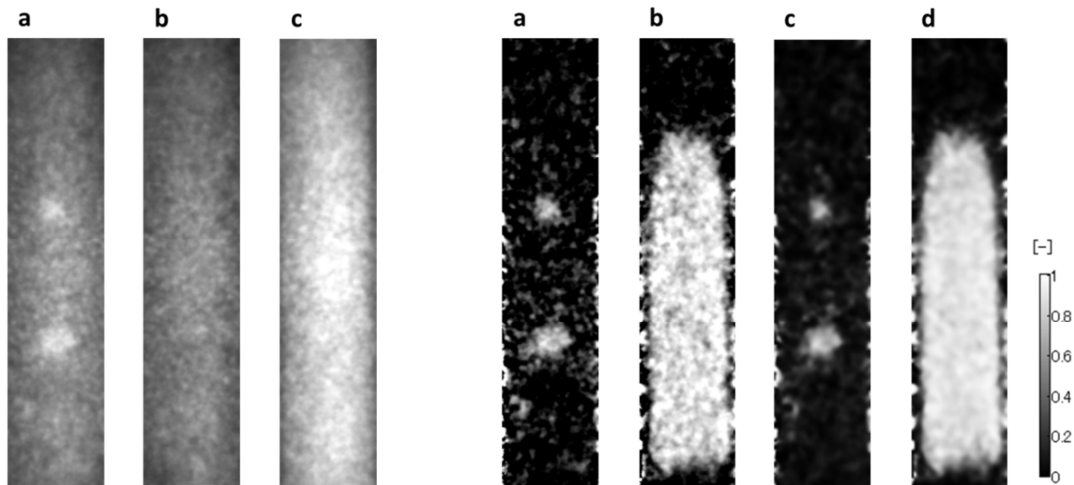


Fig. 5. Typical radiographs of (a) two-phase mixture, (b) liquid phase and (c) gas phase,

Fig. 6. Estimated void fraction distributions for (a) small bubbles and (b) large bubble, and filtered distributions for (c) small bubbles (d) large bubble.

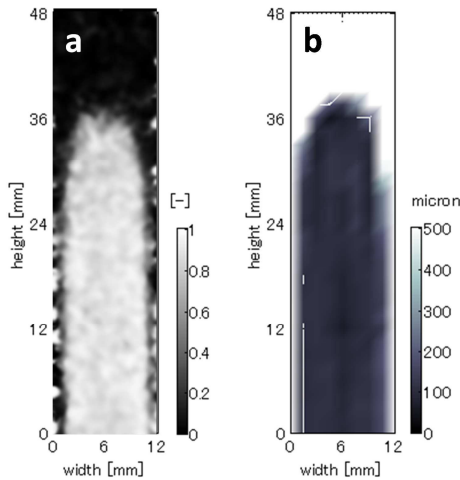


Fig. 7. Typical result of simultaneous measurement; (a) void fraction and (b) liquid film thickness distributions.

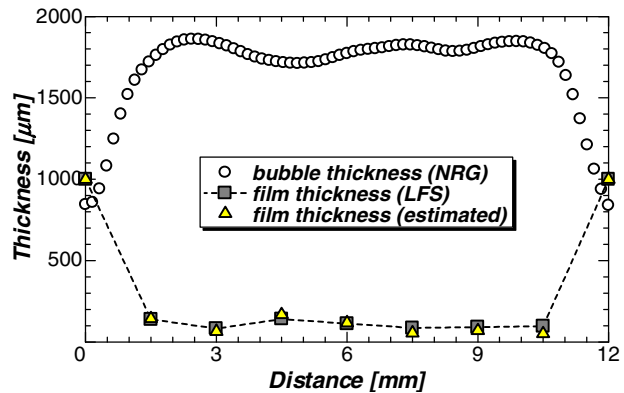


Fig. 8. Profiles of bubble thickness measured by NRG and liquid film thickness measured by LFS.

3.2. Instantaneous distributions measured by NRG and LFS

The typical result of the simultaneous measurement with NRG and LFS is shown in Fig. 7. The instantaneous distribution of the liquid film thickness between the wall and bubble could be measured, as shown in Fig. 7 (b). It is seen that measured film thickness was very thin. In addition, similar bubble shapes were found in both void fraction and film thickness distributions.

3.3. Estimation of film thickness on opposing wall

The horizontal profiles of the bubble and film thicknesses at $z = 24$ mm in the distribution shown in Fig. 7 are represented in Fig. 8. It is seen that the bubble occupies most of the gap in the channel. Thin film could be measured by LFS and the thickness was about 100 μm . The film thickness on the opposing wall, which was estimated from the measured data of NRG and LFS by Eq. (1), is also plotted in Fig. 8. This thickness profile agreed well with LFS result. Thus, the possibility of liquid film measurement on the heated surface was shown by the hybrid measurement with NRG and LFS.

4. Conclusions

A hybrid measurement method using NRG and LFS was proposed for the liquid film measurement on the heated surface and it was applied to an air-water two-phase flow measurement in a vertical narrow rectangular channel. The void fraction distribution was estimated from the dynamic neutron radiographs by Σ -scaling method and the spatio-temporal filtering was applied to remove the remarkable noises in the image. In the simultaneous measurement with NRG and LFS, the film thickness on the opposing wall which simulates the heated surface was estimated from the measured void fraction and liquid film thickness. As a result, the possibility of the liquid film measurement on the heated surface in the one-side heated narrow channel was shown.

Acknowledgements

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